LONGITUDINAL Z-BOSON PAIR PRODUCTION VIA GLUON FUSION IN TECHNICOLOR MODELS [a]

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We study the coupling of two longitudinal Z-bosons to two gluons via technicolor interactions. Noticing a similarity of this process to $2\gamma \to 2\pi^0$, we calculate the amplitude in chiral perturbation theory in one-generation technicolor model. At the invariant mass of $Z_L Z_L$ above the colored pseudo-Goldstone boson threshold, we find the signal in proton collisions at $\sqrt{s} = 14\,TeV$ is stronger than the standard model background by an order of magnitude, and is large enough to be easily observable at LHC. The cross section for $W_L^+ W_L^-$ pair production is also presented.

1 Introduction

The standard model of electroweak interactions is remarkably good in explaining numerous electroweak phenomena. However, one of its most important part, the symmetry breaking sector(SBS), remains a mystery, and its full understanding is essential to complete the theory. Numerous models were proposed as a candidate for SBS. Notable among them are the well-known minimal Higgs model, SUSY motivated models, and dynamical models such as Technicolor. It is therefore important to find effective probes of SBS and identify the right symmetry breaking mechanism. Among the many ideas proposed for this purpose, well-known are the precision measurement of the standard model, and the direct scattering of longitudinal weak gauge bosons. From the former, simplest TC models with large number of technicolors or families are already excluded.

The purpose of this talk is to show that the process $gg \to Z_L Z_L$ in proton collisions could be an effective probe of TC-type SBS. The main advantage of this process is that due to its large cross section it can be easily observable at LHC with very clean signal such as four leptons of electrons and muons. In a generic one-generation TC model, we find the signal is stronger than the standard model background by an order of magnitude. This process with an arbitrary Z-boson polarization was investigated

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in the standard model by Glover and Van Der Bij [1]. It was shown that a Higgs resonance with not too heavy mass could be easily observed through this process at proton collisions at LHC. Combining our result with Glover and Van Der Bij's, we think the Z-boson pair production via gluon fusion can be an effective probe of SBS, either elementary Higgs or TC type.

We begin our study by noticing an almost one to one correspondence between our process and $2\gamma \to 2\pi^0$. For the latter, the initial state photons produce intermediate quarks which decay into two pions via QCD interactions. Similarly, the initial state gluons in the gluon fusion process generate techniquarks which decay into longitudinal Z-bosons. By the equivalence theorem [2], the longitudinal gauge bosons may be treated as Nambu-Goldstone bosons (NGB).

The process $2\gamma \to 2\pi^0$ was first studied by Bijnens and Cornet [3], and independently by Donoghue et.al. [4] to one-loop level in chiral perturbation theory. In this talk we use one-loop chiral perturbation to estimate the cross section for $2g \to 2Z_L$. We note that the cross section was calculated in ref. [5] in chiral limit in which all the pseudo NGB masses are zero. We find in generic TC models the pseudo NGB mass effect is important, and it can give more than 200 % correction over the chiral limit result.

2   Chiral Lagrangian

Let us consider one-generation model. The model has a $SU(8)_L \times SU(8)_R$ chiral symmetry which breaks down to $SU(8)_V$, generating 63 pseudo-NGBs. As a result of the symmetry breaking, technifermions obtain approximately degenerate masses. The pseudo-NGBs comprise the color singlets

$$\Pi^a, \tilde{\Pi}^a, \Pi^D, \tag{1}$$

and the 36 colored ones

$$\Pi^\alpha, \Pi^{a\alpha}, \Pi^{\mu i}, \overline{\Pi}^{\mu i}, \tag{2}$$

where a and α are the SU(2) isospin and color octet indices respectively. The Π^as are the NGBs eaten by the weak gauge bosons.

The chiral Lagrangian in our model coupled with gluons is given in the form

$$\mathcal{L} = \frac{F_\pi^2}{4} Tr\left(D_\mu U^+ D_\mu U\right) + \mathcal{L}_m + \mathcal{L}_4 + \cdots, \tag{3}$$

with

$$\mathcal{L}_m = \frac{1}{2} Tr\left(M(U + U^+)\right), \tag{4}$$

where M is the mass matrix. The form of $\mathcal{L}_4$ is a little complicated, comprising terms involving four derivatives. The exact form may be found in standard reference [6].

Here F_π is the technipion decay constant which determines the electroweak symmetry breaking scale and is given by

$$F_\pi = \frac{v}{2} \approx 123\,GeV, \tag{5}$$

and

$$U = \exp\left(i\frac{\Pi \cdot T}{F_\pi}\right),$$

$$D_\mu U = \partial_\mu U + [G_\mu, U], \qquad G_\mu = \frac{ig_s}{\sqrt{2}}G_\mu^\alpha T^\alpha, \tag{6}$$

where T^A, $A = 1, \cdots, 63$, are the $SU(8)$ generators normalized to

$$Tr\left(T^A T^B\right) = 2\,\delta^{AB}, \tag{7}$$

and g_s, G_μ^α are the strong coupling constant and the gluon fields respectively.

Substituting (6) into (3) and expanding it, we have the desired Lagrangian

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{G-\Pi} + \mathcal{L}'_m + \mathcal{L}_\Pi, \tag{8}$$

where $\mathcal{L}_0$ is the free Lagrangian of the pseudo-NGBs. The $\mathcal{L}_{G-\Pi}$ describes pseudo-NGB coupling to gluons, and $\mathcal{L}'_m$, $\mathcal{L}_\Pi$ comprise four point interaction terms of pseudo-NGBs from the mass term and the first term in (3) respectively. They are given, in the unit $F_\pi = 1$, by

$$
\begin{aligned}
\mathcal{L}_{G-\Pi} = \quad & g_s G_\sigma^\alpha \left\{ -f^{\alpha\beta\gamma}\left(\Pi^\beta \partial_\sigma \Pi^\gamma + \Pi^{a\beta}\partial_\sigma \Pi^{a\gamma}\right) - \frac{i}{2}\lambda_{ij}^\alpha\left(\Pi_+^{\mu i}\partial_\sigma\Pi_-^{\mu j} - \Pi_-^{\mu j}\partial_\sigma\Pi_+^{\mu i}\right) \right. \\
& \left. + \frac{1}{24}\left(2f^{\alpha\beta\gamma}z^2\delta_T^{ab}\Pi^{a\beta}\partial_\sigma\Pi^{b\gamma} + i\lambda_{ij}^\alpha\delta_T^{\mu\nu}z^2\left(\Pi_+^{\mu i}\partial_\sigma\Pi_-^{\nu j} - \Pi_-^{\nu j}\partial_\sigma\Pi_+^{\mu i}\right)\right)\right\} \\
& + \frac{g_s^2}{8}G_\sigma^\alpha G_\sigma^\beta \left\{ 4f^{\alpha\gamma\tau}f^{\beta\delta\tau}\left(\Pi^\gamma\Pi^\delta + \Pi^{a\gamma}\Pi^{a\delta}\right) + \left\{\lambda^\alpha, \lambda^\beta\right\}_{ij}\Pi_+^{\mu i}\Pi_-^{\mu j} \right. \\
& \left. - \frac{z^2}{3}f^{\alpha\gamma\tau}f^{\beta\delta\tau}\delta_T^{ab}\Pi^{a\gamma}\Pi^{b\delta} - \frac{z^2}{12}\left\{\lambda^\alpha, \lambda^\beta\right\}_{ij}\delta_T^{\mu\nu}\Pi_+^{\mu i}\Pi_-^{\nu j}\right\}. \tag{9}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_\Pi = \quad & \frac{1}{24}\left\{\partial_\sigma z^2\left(\delta_T^{ab}\partial_\sigma\Pi^{a\alpha}\Pi^{b\alpha} + \delta_T^{\mu\nu}\left(\partial_\sigma\Pi^{\mu i}\Pi^{\nu i} + \partial_\sigma\overline{\Pi}^{\mu i}\overline{\Pi}^{\nu i}\right)\right) \right. \\
& - (\partial_\sigma z)^2\left(\delta_T^{ab}\Pi^{a\alpha}\Pi^{b\alpha} + \delta_T^{\mu\nu}\left(\Pi^{\mu i}\Pi^{\nu i} + \overline{\Pi}^{\mu i}\overline{\Pi}^{\nu i}\right)\right) \\
& \left. - z^2\left(\delta_T^{ab}\partial_\sigma\Pi^{a\alpha}\partial_\sigma\Pi^{b\alpha} + \delta_T^{\mu\nu}\left(\partial_\sigma\Pi^{\mu i}\partial_\sigma\Pi^{\nu i} + \partial_\sigma\overline{\Pi}^{\mu i}\partial_\sigma\overline{\Pi}^{\nu i}\right)\right)\right\}. \tag{10}
\end{aligned}
$$

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\begin{aligned}
\mathcal{L}'_m = \quad & \frac{z^2}{96}\left(3Tr\left(M(\Pi^\alpha)^2\right) + (2\delta^{ab} + \chi^{ab})Tr\left(M\Pi^{a\alpha}\Pi^{b\alpha}\right) + \right. \\
& \left. (2\delta^{\mu\nu} + \chi^{\mu\nu})Tr\left(M\left(\Pi^{\mu i}\Pi^{\nu i} + \overline{\Pi}^{\mu i}\overline{\Pi}^{\nu i}\right)\right)\right) \\
= \quad & \frac{z^2}{48}\left(3m_\alpha^2(\Pi^\alpha)^2 + m_{a\alpha}^2(2\delta^{ab} + \chi^{ab})\Pi^{a\alpha}\Pi^{b\alpha} + \right. \\
& \left. m_{\mu i}^2(2\delta^{\mu\nu} + \chi^{\mu\nu})\left(\Pi^{\mu i}\Pi^{\nu i} + \overline{\Pi}^{\mu i}\overline{\Pi}^{\nu i}\right)\right), \tag{11}
\end{aligned}
$$

where

$$\Pi_\pm^{\mu i} = \frac{1}{\sqrt{2}} \left(\Pi^{\mu i} \mp i\overline{\Pi}^{\mu i} \right), \tag{12}$$

and Π^A inside the trace should be regarded as $\Pi^A \cdot T^A$. In deriving (11), we have used the fact that $(T^a)^2 \sim I$, and thus commute with all the generators, and

$$Tr\left(M(\Pi^A)^2 \right) = 2m_A^2 \, (\Pi^A)^2, \tag{13}$$

which is from the quadratic mass terms of pseudo-NGBs. Note that $\mathcal{L}'_m$ is completely parameterized in terms of the pseudo-NGB masses, independently of the detailed form of M. We also note that in (9), (10) and (11), only terms relevant for our process are presented and $z \equiv \Pi^3$ is the NGB eaten by Z-boson. The tensors are defined by

$$\delta_T^{ab} = \mathrm{Diag}(1,1,0), \delta_T^{\mu\nu} = \mathrm{Diag}(0,1,1,0)$$
$$\chi^{ab} = \mathrm{Diag}(-1,-1,1), \chi^{\mu\nu} = \mathrm{Diag}(1,-1,-1,1). \tag{14}$$

3 Z_L-pair production rate

With the Lagrangian given in sec.2, it is straightforward to calculate the one-loop amplitude for $2g \to 2Z_L$. Since the details of calculation are very similar to those for $2\gamma \to 2\pi^0$ and they can be found in ref.[4], we present here only the final result for $G_\mu^\alpha(q_1)G_\mu^\alpha(q_1) \to 2z$, which is given by

$$A_{\mu\nu}^{\alpha\beta}(q_1, q_2) = \frac{g_s^2}{F_\pi^2} \left(\frac{-i}{16\pi^2} \right) \delta^{\alpha\beta} \left(\frac{g_{\mu\nu} q_1 \cdot q_2 - q_{2\mu} q_{1\nu}}{q_1 \cdot q_2} \right) \cdot \mathcal{A}(s), \tag{15}$$

where

$$\begin{aligned}
\mathcal{A}(s) &= \frac{3}{4} m_\alpha^2 \left(1 + 2I(m_\alpha, s) \right) \\
&+ \frac{3}{2} \left(s + \frac{1}{6} m_{a\alpha}^2 - \frac{2}{3} m_z^2 \right) \left(1 + 2I(m_{a\alpha}, s) \right) \\
&+ \frac{1}{2} \left(s + \frac{2}{3} (m_{\mu i}^2 - m_z^2) \right) \left(1 + 2I(m_{\mu i}, s) \right),
\end{aligned} \tag{16}$$

with $s = (q_1 + q_2)^2$ and

$$\begin{aligned}
I(m, s) &= \int_0^1 \frac{m^2}{xys - m^2 + i\epsilon} \theta(1 - x - y) dx dy \\
&= \frac{m^2}{2s} \left(\ln\left(\frac{1 + \sqrt{1 - \frac{4m^2}{s}}}{1 - \sqrt{1 - \frac{4m^2}{s}}} \right) - i\pi \right)^2 \quad \text{for } s > 4m^2, \\
&= -\frac{m^2}{2s} \left(\pi - 2\arctan\sqrt{\frac{4m^2}{s} - 1} \right)^2 \quad \text{for } s < 4m^2.
\end{aligned} \tag{17}$$

Figure 1: The cross sections for Z_L-pair and W_L-pair production via gluon fusion in proton collisions at $E_{c.m.} = 14\,TeV$. The solid lines are for the $q\bar{q}$ backgrounds, and dotted, dot-dashed, and dashed lines are for the pseudo Nambu-Goldstone boson mass of $250\,GeV$, $300\,GeV$, and $350\,GeV$ respectively. The thick dot-dashed lines are for the chiral limit.

The cross section using the fitted parton distribution functions for MRSA [7] is plotted in Fig.1 in the range $200\,GeV \leq \sqrt{\hat{s}} \leq 1\,TeV$ with the rapidity cut $|y| \leq 2.5$, and over the standard model background for several values of the pseudo-NGB masses. For simplicity, we put identical values for the colored pseudo-NGB masses. The main sources of the background are the quark fusion $q\bar{q} \to ZZ$ and the gluon fusion $gg \to ZZ$ via fermionic one-loop interactions. The quark fusion is the dominant background at LHC energies as shown in ref.[1], and it is about three times stronger than the gluon fusion in the invariant mass range considered above. In Fig.1a we observe that our signal at energies below the pseudo-NGB threshold is negligible relative to the background, but above the threshold larger than the background by a factor of $O(7-40)$ depending on the energy. Notice that the pseudo NGB mass effect is still important at energies above the pseudo NGB threshold and it can enhance the cross section by a facor two. As expected, the signal to background ratio becomes larger as the invariant mass increases. This is mainly because the four-point vertices of pseudo NGBs from the lagrangian $\mathcal{L}_\Pi$ in (10) are proportional to the invariant mass. Since our signal is so strong, it will increase the overall Z-boson pair production rate above the pseudo-NGB threshold, and this obviates the need to measure the polarization of the final state Z-bosons.

We also plot the cross section for $W_L^+ W_L^-$ pair production via gluon fusion. Be-

cause of the $SU(2)$ isospin symmetry the amplitude for $gg \to W_L^+ W_L^-$ is exactly given by Eq. (16) with m_z replaced by m_w, and the cross section is approximately twice that of Z_L pair production. The dominant background for the W_L pair production is also the $q\bar{q}$ fusion. From Fig.1b we see that the signal above the colored pseudo NGB threshold is stronger than the background by a factor of $O(6-40)$. Notice that we have applied a more stringent rapidity cut, $|y| \le 1.5$, to enhance the signal to background ratio.

Clearly the signal should be observable without difficulty at LHC with the planned c.m. energy $\sqrt{s} = 14\,TeV$ and the integrated luminosity $100\,fb^{-1}$ per year. As an example, let us consider the Z_L-pair production via gluon fusion with the pseudo NGB mass of $300\,GeV$. The integrated cross section with the invariant msss above the pseudo NGB threshold is $\sigma(\sqrt{\hat{s}} \ge 600\,GeV) = 3.4\,pb$. The most clean signal for the Z_L-pair production would be four leptons of electrons and muons without jets. With the branching ratio of .45%, the event rate would be 1530 per year. Instead if the signal is two leptons of electrons or muons with missing mass, then the event rate would be 9180 per year. This shows that our process could be an effective probe of SBS of TC type with pseudo NGBs having nonzero color and electroweak isospin.

1. E.W.N. Glover and J.J. Van Der Bij, Nucl. Phys. B 321 (1989) 561.
2. M.S. Chanowitz and M.K. Gaillard, Nucl. Phys. B 261 (1985) 379
3. J. Bijnens and F. Cornet, Nucl. Phys. B 296 (1988) 557.
4. J.F. Donoghue, B.R. Holstein and Y.C. Lin, Phys. Rev. D37 (1988) 2423.
5. J. Bagger, S. Dawson, and G. Valencia, Phys. Rev. Lett. 67 (1991) 2256.
6. J. Gasser and H. Leutwyler, Ann. Phys. (NY) 158 (1984) 142; Nucl. Phys. B 250 (1985) 465.
7. A. D. Martin, R.G. Roberts and W.J. Stirling, Phys. rev. D50 (1994) 6734.